The Low-force Sample Acquisition System

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***Abstract* - Current science for Mars and lunar exploration demands that rock fines from a wide variety of rock types ranging from soft shale to very hard basalts be acquired for geologic evaluation. Tools to acquire these samples must be light weight, draw minimal power, and induce low loads on their robotic platforms. The drills and other sample acquisition systems that have been produced to date do not meet one or more these requirements.**

Alliance Spacesystems, LLC (Alliance) produced a rotary percussive drill designed for light weight space robotic arms and rovers under a NASA-funded Mars Instrument Development Program (MIDP) project – the Low-force Sample Acquisition System (LSAS). The flight-like drill prototype that was the end result of the project successfully drilled and acquired 1 cm³ samples from a variety of rocks and soils including the hardest anticipated Martian rock (basalt) and frozen soil. This ability was demonstrated not only in ambient conditions but also in a thermal/vacuum chamber replicating Mars pressure and extreme temperatures.

The LSAS drill design, though derived from extensive analysis and empirical testing, is simple in concept and operation. The drill is driven by a single electric motor that rotates the bit and drives the rotary cam hammer mechanism. To operate, the LSAS is pressed against the target with a force of approximately 35 N, compressing a seal and internal preload spring and activating a position sensor that indicates the preloaded position. Drilling begins and fines are transported by the fluted bit into a sample bin. Once the bit has extended to a predetermined depth that will yield the appropriate sample size, another position sensor is tripped and drilling ceases. The sample bin is then pushed against an instrument container orifice, forcing open spring-preloaded sections and ejecting the sample. The complete LSAS unit weighs 440 g and requires less than 20W to operate.

The paper includes discussions on current percussive drilling practice, the theoretical approach to establishing percussive drilling parameters, background testing on Mars stimulant samples, and a description of the prototype design and performance tests.

I. INTRODUCTION

A significant amount of research has previously been conducted in the field of drilling and near-surface material removal. The Low-force Sample Acquisition System (LSAS) effort by Alliance Spacesystems, LLC (Alliance) extended that work to provide a realistic system for readily acquiring samples from almost any rock or soil target and delivering them from any platform to a suite of instruments. LSAS adds an important feature set to future missions that may already be planning some form of sample acquisition but need the capability to acquire fines or small chips from assorted targets at various depths. This work represents the final step necessary in developing such hardware suitable for use on Mars. Data from the extensive testing performed under this effort demonstrates the effectiveness of such systems and will directly aid the planning of future missions and sample acquisition mechanisms. Finally, hardware developed under this proposal is available to JPL and others to conduct systems-level rover and lander operations in a simulated Martian environment.

LSAS can contribute directly to several NASA missions planned for the immediate future including the Mars Science Laboratory (MSL), Mars Scouts, and Mars Sample Return (MSR). It is a natural extension to previous work and brings the technology to a level suitable for flight on these future missions.

II. PROGRAM GOALS AND BACKGROUND

Sample acquisition will be an essential function of all future Mars landers including MSL, Mars Scouts, and MSR. The LSAS is intended to be a flexible tool capable of being utilized on any and all of these missions. The project set out to accomplish the following objectives:

- Deliver a second-generation sample acquisition mechanism based on existing hardware concepts but specifically designed to be flight-ready, smaller, and lighter while, at the same time, drawing less power.
- Provide a mechanism capable of retrieving a 1 cm³ sample of soil, rock, or ice from the Martian surface, subsurface, or a borehole.
- Provide a system usable on a wide variety of platforms including robotic arms, large and small rovers, drills, or other instrument positioning devices.
- Develop a mechanism capable of all of the above while operating with very little applied force (originally < 4.5N) allowing use by flexible instrument positioning devices and lightweight rovers.
- Build on the heritage of existing systems and lessons learned from those systems. In particular:

Alliance experience in developing the Instrument Deployment Device (IDD) for the Mars Exploration Rover project [1]; Alliance experience in developing the Sub-Surface Explorer (SSX) drill for JPL [2]; and heritage from the rock grinder/corer and MOLE mechanisms flying on the Beagle 2 lander as part of ESA's Mars Express mission [3].

- Deliver samples of a very specific volume and particle size to the lander instruments.
- Increase the Technology Readiness Level of the available hardware to Level 6.

III. DEVELOPMENT

A multi-stage development program was implemented that combined extensive laboratory experiments with background analysis and design iterations. The program was designed to maximize cost and schedule efficiency by best utilizing commercial-off-the-shelf (COTS) hardware before committing to flight-capable custom hardware. Early testing using commercial hardware coupled with analysis led to more specific evaluations using a breadboard fixture, finally culminating in the design, fabrication and test of a flight-like prototype.

A. Commercial-Off-The-Shelf Drill

During the initial stage of the program current Mars state of the art and relevant commercial drilling practice were reviewed with regards to drill bits and hammer drills Commercial bits using configurations similar to candidate Mars configurations were procured along with a COTS hammer drill. This drill was modified for the initial tests by making force and speed adjustable and integrating it with a programmable power supply as shown in Fig. 1. These initial tests determined the most promising combinations of parameters for drilling representative rock samples including bit type, hammer and down force, and rotational speed.

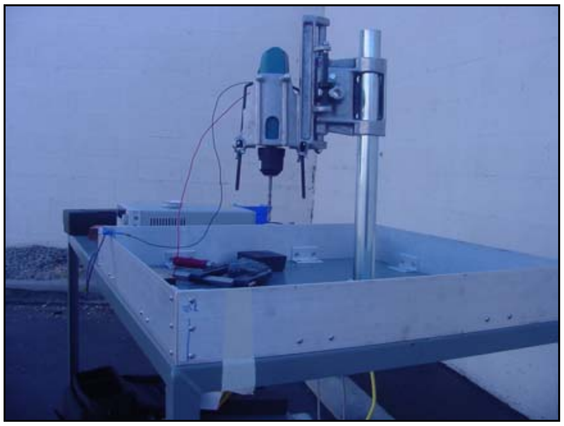

Fig. 1. COTS Drill Fixture.

B. Breadboard Fixture

After the completion of initial testing a breadboard drill fixture was then developed. This fixture shown in Fig. 2 included the basic hammer drill features but allowed bits to be readily interchanged and enabled variations in hammer force, applied force, hammer frequency and rotational speed. This flexibility enabled the best candidate design configurations and force and speed settings to be rapidly evaluated and compared. An attempt was also made to develop a correlated impact model to size the mass and spring for the hammer mechanism.

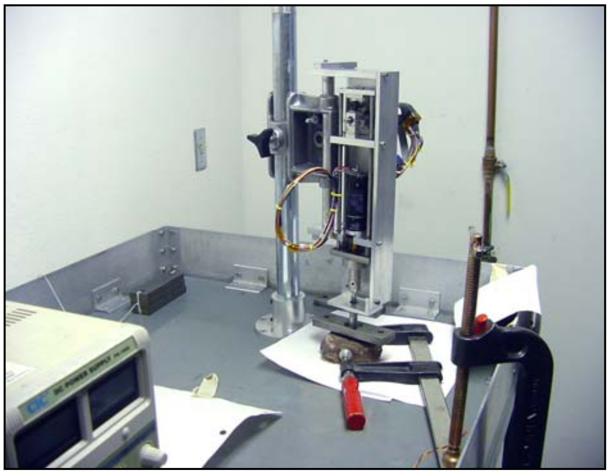

Fig. 2. Breadboard Drill Fixture.

Two different types of data summary are shown in the figures below. Fig. 3 shows the differences in performance of various design bits when used under identical conditions against basalt.

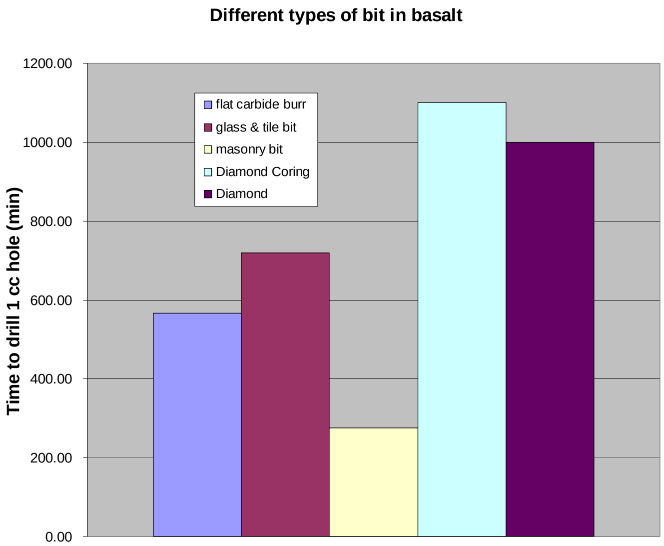

Fig. 3. Typical Breadboard Test Results Summary.

Fig. 4 shows the effect of hammer frequency on drilling rate using the same drill bit and keeping all other performance parameters the same.

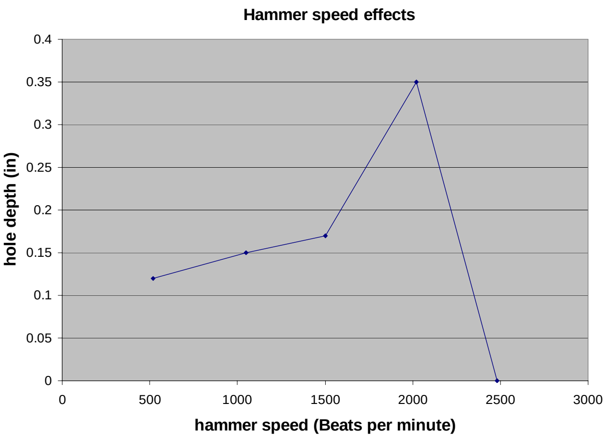

Fig. 4. Effect of Hammer Frequency on Drilling Rate

The open nature of the test fixture also enabled multiple configurations of candidate sample bin designs to be evaluated in an expeditious manner.

C. Final Design

The early conceptual design developed for the proposal was continually refined during the initial test phases as more insight was gained into the performance of the system. Finally using the knowledge gained from the dozens of tests performed during the breadboard stage, the baseline detail design of the three primary components in the system (bits, percussive drill, and sample bin) was completed. Two versions were designed – a baseline and a heavy version – due to concerns regarding motor capability. Only the baseline version was actually assembled and tested.

The resulting LSAS is a percussive drill with integral sample acquisition intended to drill into a wide variety of rocks and frozen soils. The simple and elegant mechanism uses a single motor to acquire samples by drilling into the surface of a target material. The drill bit (a two-blade percussive bit made of very specific materials to ensure life and minimize contamination issues) is driven by a space-qualified brushless DC motor with a planetary speed reducer. The drilling action is hammer driven, allowing the mechanism to acquire a sample with the minimum amount of force necessary. The hammer is actuated by a spring/free mass system driven by the motor and a cam-follower. As material is removed from the target surface or hole it is fed into the mechanism by the bit flutes which deposit the sample into a storage bin via holes for later delivery to the support platform's instruments. A cutaway of the mechanism is shown in Fig. 5.

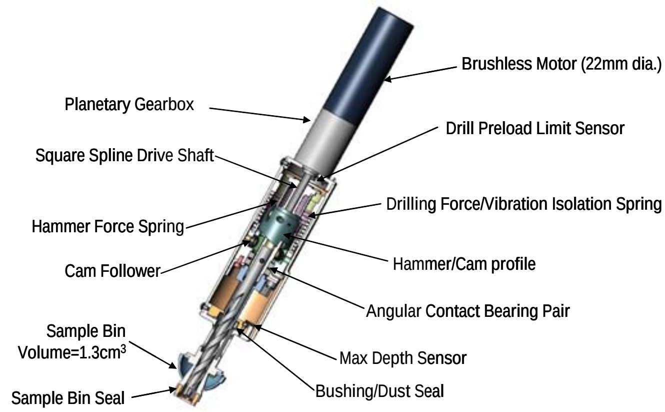

Fig. 5. Effect of Hammer Frequency on Drilling Rate.

LSAS operation is straightforward and readily autonomous. First, the sampling tool is placed against a target. Preload is set and maintained by compressing an internal spring that supports the hammer drill system. Redundant contact sensors indicate that the bit has been depressed to the correct position, automatically resulting in the tool being placed against the target with the correct amount of force. Once in position, the motor spins the bit at approximately 800 rpm and the bit begins to drill into the surface of the target. Hammering action is the primary drilling effect and occurs three times per revolution. The hammering action is driven by the same motor and is accomplished via the cam-follower that forces the hammer up as it rotates, compressing a spring, and then releases the stored energy very quickly, driving the bit into the target. As material is removed it is carried into the mechanism by the fluted bit as shown in Fig. 6. Material travels up the flutes and is forced into the sample bin by brushes riding along the side of the gaps between the flutes. The sample bin gradually fills to the desired volume and any excess material simply travels past the bin and out of the mechanism.

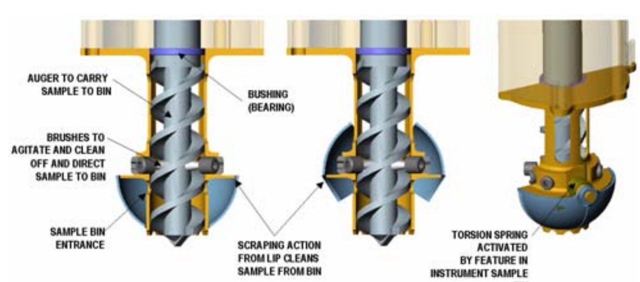

Fig. 6. Material Transport into Sample Bin.

Once the required amount of sample is acquired, it can be delivered to any instrument on the support platform. To allow for sample delivery, the LSAS incorporates a passive clamshell storage bin. Features on each instrument (also developed as part of this effort) force the clamshell open as the tool comes into contact with the instrument. A simple scraper ensures all material is removed from the bin as it is opened and actuating the hammer a few times helps remove particularly cohesive material, minimizing cross-contamination between samples.

The LSAS prototype unit was subjected to extensive functional testing to verify its ability to generate and retrieve samples from Mars analog targets including shale and basalt. Fig. 7 shows the prototype in a typical test configuration.

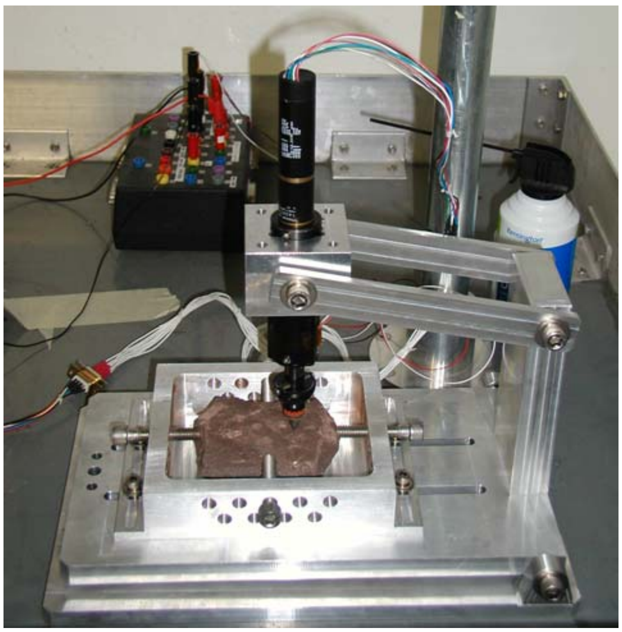

Fig. 7. LSAS Prototype in Functional Test.

The unit was also subjected to environmental testing including chamber testing that replicated Mars temperatures and pressures in order to establish Technology Readiness Level 6. Rock (shale and basalt), compacted soil and frozen soil were successfully sampled under these conditions. The project culminated in a series of tests at the Jet Propulsion Laboratory's (JPL's) Mars Yard, during which the unit was mounted to the robotic arm of the Jet Propulsion Laboratory's Rocky 8 test rover as shown in Fig. 8. The ability to sample from this lightweight platform was successfully demonstrated, proving the feasibility of LSAS for future Mars missions utilizing lightweight robotic platforms. Table 1 summarizes the basic LSAS characteristics for both the baseline and heavy versions.

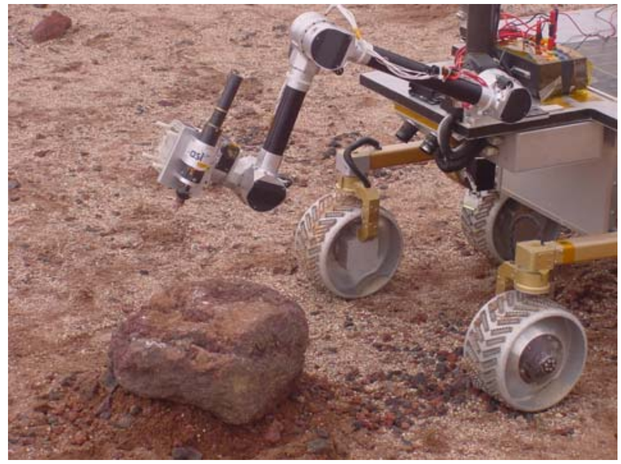

Fig. 8. LSAS Prototype Mounted to JPL's Rocky 8 Rover.

Table 1. LSAS Characteristics.

Parameter	Units	LSAS (Basic)	LSAS (Heavy)
Mass	g	440	550
Length	mm	229	260
Diameter	mm	33	33
Drill Diameter	mm	6.35	6.35
Drill Depth	mm	19	19
Sample Volume	cm^3	1.5	1.5
Core Diameter	mm	N/A	N/A
Core Length	mm	N/A	N/A
Power	W	15-20	40-50
Penetration Rate	cm/hr	2	5
Hold Down Force	N	35	148
Operational Temperature Range	°C	-120/+35°C	-120/+35°C
Survival Temperature Range	°C	-135/+110°C	-135/+110°C
Pressure Range	torr	0-760	0-760
Life	samples	75	75

IV. LESSONS LEARNED

In general, the development and testing of the LSAS unit was quite trouble-free. The overriding area of concern was the interface between the bit and drill which transfers not only the impact from the hammer but also rotation. The original design imparted rotation by means of a round hardened steel pin riding in a slot machined into the drill shank. The slot was intended to allow free linear motion of the bit after hammer impact, crucial to effective drilling. While the design worked effectively initially, drill rate was found to degrade fairly quickly and disassembly revealed that the pin was deforming the sides of the slot. This deformation impeded free travel, turning the system in effect into a simple rotational drill and significantly degrading the efficiency of operation as sown in Fig. 9.

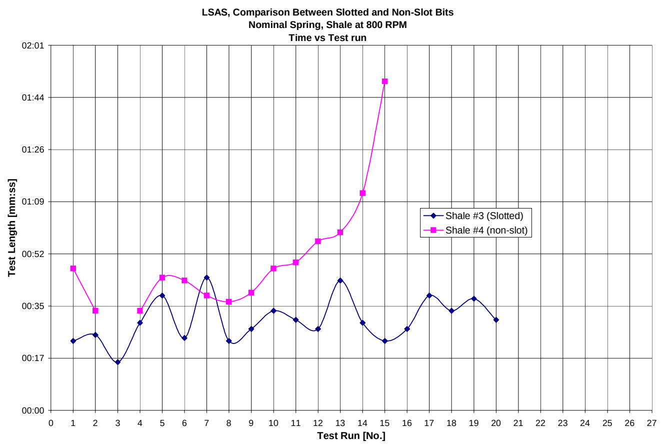

Fig. 9. Effect of Deformed Slot on Drilling Rate.

Unfortunately a rigorous solution that would eliminate the problem outright could not be readily implemented due to limitations of cost and schedule. An interim solution was to replace the round pin with a square pin, significantly increasing the area of contact between the pin and drill shank. However this produced only a minor increase in life, with deformation still resulting in limited bit life. The ultimate solution to be implemented at the next opportunity will be to replace the pin/slot approach and impart rotation by driving through a square or spline bit shank, actually similar to commercial practice, dramatically improving the load transfer capability and yielding a far more robust design.

Other lessons learned were in comparison second order observations. First, bits of almost all configurations and drilling into almost all materials were observed to wear significantly during their first use but then immediately stabilize into a gradual wear profile. A second observation involved the choice of drill test samples. Variations in test results without apparent explanation were noticed in many early tests. Variability between test samples of the same materials were to blame, since rocks even from the same purchased batch showed variations in density (particularly the softer rock) and many samples included internal cracks and fractures. For a more qualitative assessment when evaluating design options and operating parameters, a more homogenous material such as hard brick or concrete is required to provide consistent results. After these trades are completed the system can then be verified against the anticipated Mars analog materials.

V. FUTURE WORK

The light weight, low force and comparatively low power requirements of the LSAS system make adapting the device for other functions desirable. In an effort internally funded by Alliance the original LSAS drill was modified to accommodate a commercial off the shelf hole saw whose shaft could be adapted to fit the LSAS interface. The pilot bit was removed from the center of the hole saw to create a small (1.5 cm diameter) coring bit. Though no attempt was made to optimize the system, it performed remarkably well in soft rock. As a result of this promising initial work Alliance Spacesystems was recently awarded a Small Business Innovation Research (SBIR) contract to further adapt LSAS for coring. As part of this effort an improved coring bit will be defined, the mechanism will be resized as appropriate, and mechanisms for cuttings removal, core break off and core handling will be added. The project will complete in July 2007.

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REFERENCES

1. Fleischner, R. 2003, ‘Development of the Mars Exploration Rover Instrument Deployment Device’, Alliance Spacesystems, Inc.
2. Wilcox, B. 2001, ‘Subsurface-Explorer Robot with Spinning Hammer Drive’, NASA Tech Briefs, October, NPO-20614.
3. Ng, T.C. & Yung, K.L. 2002, ‘Mars Rock Corer and Planetary Micro Sampling Tools’, Proceedings of the 33rd Lunar and Planetary Science Conference, Lunar and Planetary Institute, Houston, TX.